# On the evolution of the nuclear modification factors with rapidity and centrality in d+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$

I. Arsene[10], I. G. Bearden[7], D. Beavis[1], C. Besliu[10], B. Budick[6], H. Bøggild[7], C. Chasman[1], C. H. Christensen[7], P. Christiansen[7], J. Cibor[3], R. Debbe[1], E. Enger[12], J. J. Gaardhøje[7], M. Germinario[7], K. Hagel[8], H. Ito[1], A. Jipa[10], F. Jundt[2], J. I. Jørdre[9], C. E. Jørgensen[7], R. Karabowicz[4], E. J. Kim[1,11], T. Kozik[4], T. M. Larsen[12], J. H. Lee[1], Y. K. Lee[5], S. Lindal[12], R. Lystad[9], G. Løvhøiden[12], Z. Majka[4], A. Makeev[8], M. Mikelsen[12], M. Murray[8,11], J. Natowitz[8], B. Neumann[11], B. S. Nielsen[7], D. Ouerdane[7], R. Płaneta[4], F. Rami[2], C. Ristea[10], O. Ristea[10], D. Röhrich[9], B. H. Samset[12], D. Sandberg[7], S. J. Sanders[11], R. A. Scheetz[1], P. Staszel[7], T. S. Tveter[12], F. Videbæk[1], R. Wada[8], Z. Yin[9], and I. S. Zgura[10]
The BRAHMS Collaboration

[1] Brookhaven National Laboratory, Upton, New York 11973
[2] Institut de Recherches Subatomiques and Université Louis Pasteur, Strasbourg, France
[3] Institute of Nuclear Physics, Krakow, Poland
[4] Smoluchkowski Inst. of Physics, Jagiellonian University, Krakow, Poland
[5] Johns Hopkins University, Baltimore 21218
[6] New York University, New York 10003
[7] Niels Bohr Institute, Blegdamsvej 17, University of Copenhagen, Copenhagen 2100, Denmark
[8] Texas A&M University, College Station, Texas, 17843
[9] University of Bergen, Department of Physics, Bergen, Norway
[10] University of Bucharest, Romania
[11] University of Kansas, Lawerence, Kansas 66049
[12] University of Oslo, Department of Physics, Oslo, Norway

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We report on a study of the transverse momentum dependence of nuclear modification factors $R_{dAu}$ for charged hadrons produced in deuteron + gold collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, as a function of collision centrality and of the pseudorapidity ($\eta = 0, 1, 2.2, 3.2$) of the produced hadrons. We find a significant and systematic decrease of $R_{dAu}$ with increasing rapidity. The midrapidity enhancement and the forward rapidity suppression are more pronounced in central collisions relative to peripheral collisions. These results are relevant to the study of the possible onset of gluon saturation at RHIC energies.

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Studies of deep inelastic scattering of leptons on hadronic systems (protons and nuclei) have revealed a large component of gluons in the nuclear systems with small–$x$ (i.e. fraction of the nucleon momentum) that appears to diverge with decreasing $x$ [1]. However, it has also been suggested that the density of gluons remains finite due to the increased role of gluon-gluon correlations ('gluon fusion'), forcing an upper limit on the total number of highly delocalized small–$x$ gluons [2, 3]. Phenomenological descriptions of HERA and FNAL results [4, 5] based on gluon saturation appear to successfully describe the data. As a consequence, nuclei at high energies may be thought of as highly correlated systems of small–$x$ gluons. A QCD based theory for dense small–$x$ systems, termed the Color Glass Condensate (CGC) has been developed [6].

Collisions between hadronic systems at center-of-mass energy $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ at the at the Relativistic Heavy Ion Collider (RHIC) provide a window on the small–$x$ gluon distributions of swiftly moving nuclei. In particular, collisions between deuterons and gold nuclei in which hadrons with $p_T > 1\mathrm{GeV/c}$, mostly produced by quark–gluon interactions, are detected close to the beam direction but away from the direction of motion of the gold nuclei, allow one to probe the small–$x$ components of the wave function of the gold nuclei. It has been predicted that gluon saturation effects will manifest themselves as a suppression in the transverse momentum distribution below a value that sets the scale of the effect [6–8]. The transverse momentum scale for the onset of gluon saturation depends on the gluon density and thus on the number of nucleons, and is connected with the rapidity $y$ of measured particles by $Q_s^2 \sim A^{\frac{1}{3}} e^{\lambda y}$. Where $\lambda \sim 0.2 - 0.3$ is obtained from fits to HERA data. Thus saturation effects are most evident at large $y$ or pseudorapidity $\eta$, i.e. at small angles relative to the beam direction.

We report measurements of transverse momentum spectra of hadrons from p+p and d+Au collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$ in four narrow pseudorapidity ranges around $\eta = 0$, 1, 2.2, and 3.2 (where the rapidities of the deuteron and the gold nucleus is +5.4 and −5.4, respectively). Results around midrapidity have previously been reported [9, 10].

These covered ranges would correspond to probing the

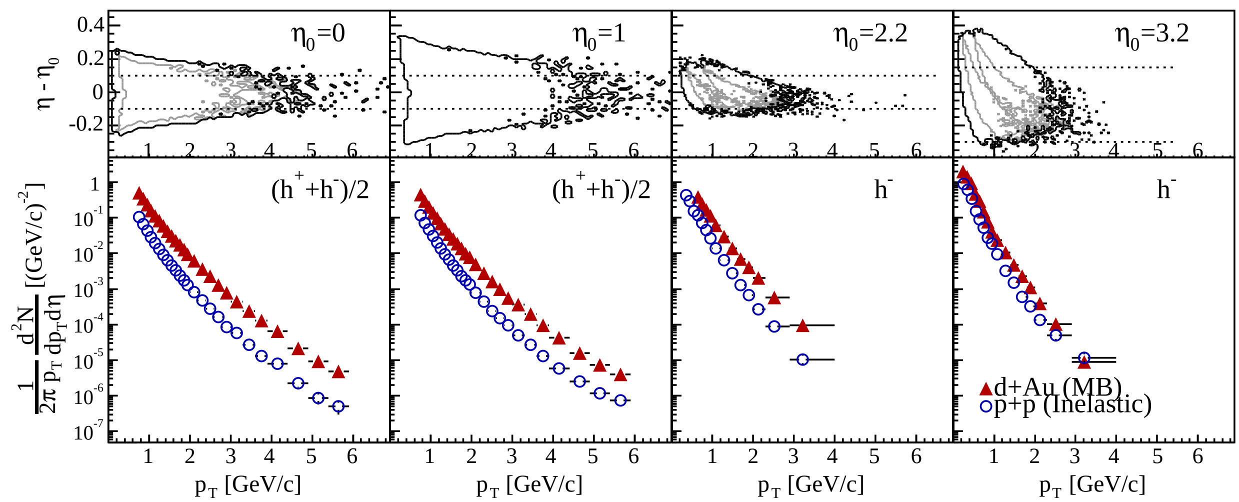


FIG. 1: Bottom row: Invariant yield distributions for charged hadrons produced in d+Au and p+p collisions at $\sqrt{s} = 200\,\text{GeV}$ at pseudorapidities $\eta = 0, 1.0, 2.2, 3.2$ Horizontal lines indicate bin width. Top row: Outline of the combined acceptance in $\eta$ vs $p_T$ of the BRAHMS spectrometers at the various angle and magnetic field settings (shifted in $\eta$). The dotted lines indicate the cuts applied in $\eta$.

gluon structure of the gold nuclei (with $p_T = 2\,\text{GeV/c}$ pions) in an $x$ range from 0.01 to $4 \times 10^{-4}$. We compare the yields from d+Au collisions to those from p+p, scaled by the average number of binary collisions $\langle N_{coll} \rangle$ in a d+Au event.

The data presented here for d+Au and p+p collisions were collected with the BRAHMS detector system, consisting of event characterization detectors and two magnetic spectrometers, the Forward Spectrometer (FS) and the Mid-Rapidity Spectrometer (MRS), which can be rotated in the horizontal plane around the direction defined by the colliding beams. For the present studies the MRS was positioned at 90 and 40 degrees and the FS at 12 and 4 degrees with respect to the beam direction. The orientation of the beams was such that the spectrometers measured particles emitted on the deuteron fragmentation side.

A description of the BRAHMS experimental setup can be found in ref. [11]. The experimental method and analysis techniques employed here are similar to those used for the study of d+Au and Au+Au collisions [10], except that the present data at $\eta = 2.2$ and $\eta = 3.2$ were analyzed using the front part of the FS detector systems only.

The minimum bias trigger is estimated to select $91\% \pm 3\%$ of the d+Au inelastic cross section and $71\% \pm 5\%$ of the total inelastic proton-proton cross section of 41 mb. The measured p+p yields have been corrected for the experimental trigger bias, our trigger selects non-single-diffractive events and we estimate using the PYTHIA model that the correction should be $13 \pm 5\%$, approximately independent of $p_T$ and $\eta$.

Figure 1 shows the invariant yields of charged hadrons obtained from d+Au collisions and p+p collisions in narrow pseudorapidity intervals around $\eta = 0, 1, 2.2$ and 3.2. The FS was set up to measure negatively charged particles; the spectra at $\eta = 2.2$ and 3.2 are for negative hadrons only. The top panels show the outline of the corresponding acceptances of the spectrometers for the employed settings, in terms of $\eta$ and transverse momentum $p_T$. Each distribution was constructed from independent measurements at several magnetic field settings, and is corrected for the spectrometer acceptance and tracking efficiency. No corrections for the finite momentum resolution, absorption or weak decays have been applied, the 15% systematic error on the spectra includes the contribution from these effects. The momentum resolution of the spectrometers at the maximum magnetic field setting is $\delta p/p = 0.0077p$ for the MRS and $\delta p/p = 0.0018p$ for the FS, where p is written in units of GeV/c.

In Fig. 2 we compare the d+Au spectra to normalized p+p distributions using the nuclear modification factor defined by:

$$R_{dAu} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N^{d+Au}/dp_T d\eta}{d^2 N^{p+p}_{inel}/dp_T d\eta}. \qquad (1)$$

Inherent in this definition is the assumption that the production of moderately high transverse momentum particles ($p_T \gtrsim 2\,\text{GeV/c}$) scales with the mean number of binary collisions $\langle N_{coll} \rangle$. For our d+Au minimum–bias sample we estimate $\langle N_{coll} \rangle = 7.2 \pm 0.3$, using the HIJING v.1.383 event generator [12] and a GEANT based Monte-Carlo simulation of the experiment. In the presented ratios most systematic errors cancel out. Remaining systematic errors arising from variations in collision vertex distributions, trigger efficiencies and background conditions etc. are estimated to be less than 10% at $\eta = 0$ and less than 15% at all other angle settings. Based on simulations of p+p at forward angles we can state that

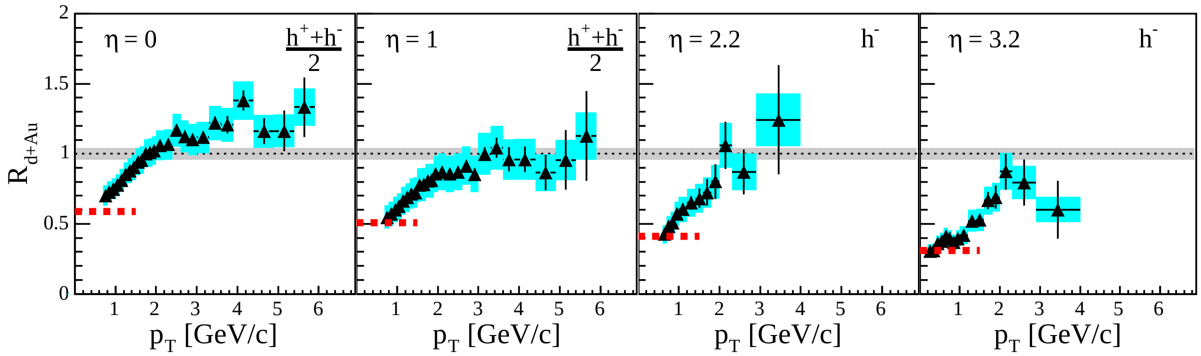


FIG. 2: Nuclear modification factor for charged hadrons at pseudorapidities $\eta = 0, 1.0, 2.2, 3.2$. One standard deviation statistical errors are shown with error bars. Systematic errors are shown with shaded boxes with widths set by the bin sizes. The shaded band around unity indicates the estimated error on the normalization to $\langle N_{coll} \rangle$. Dashed lines at $p_T < 1$ GeV/c show the normalized charged particle density ratio $\frac{1}{\langle N_{coll} \rangle}\frac{dN/d\eta(Au)}{dN/d\eta(pp)}$.

the ratios calculated with negative particles are greater than the ones calculated with the average $(h^+ + h^-)/2$.

Figure 2 reveals a clear variation of the $R_{dAu}$ as a function of pseudorapidity. At midrapidity, $R_{dAu}(p_T > 2\,\mathrm{GeV/c}) > 1$ evidencing an enhancement as compared to the binary scaling limit. This so–called Cronin enhancement is attributed to multiple scattering of partons during the collisions resulting in an accumulation of the yield of the final state partons in the $p_T$ range $2 - 5\,\mathrm{GeV/c}$, at the expense of yield at lower $p_T$ [13]. At $\eta = 1$ the Cronin peak is not present and at more forward rapidities ($\eta = 3.2$) the data show a suppression of the hadron yields. A rise with $p_T$ in the range of $0.5 - 3$ GeV/c is observed at all rapidities. There is a strong correlation between the values of the $R_{dAu}$ at low $p_T$ and the ratio of charged-particle pseudorapidity densities in d+Au and p+p collisions $\frac{1}{\langle N_{coll} \rangle}\frac{dN/d\eta(Au)}{dN/d\eta(pp)}$ shown in Fig. 2 with dashed lines at $p_T < 1 GeV/c$ [19, 20].

Figure 3 shows the ratio $R_{cp}$ of yields from collisions of a given centrality class (0-20% or 30-50%) to yields from more peripheral collisions (60-80%), scaled by the mean number of binary collisions in each sample. The centrality selection is based on charged particle multiplicity in the range $-2.2 < \eta < 2.2$ as described in [19]. Assuming that the nuclear modification is relatively small in the peripheral collisions the deviation from unity of the $R_{cp}$ is dominated by the nuclear effects in the more central collisions. The $R_{cp}$ ratios thus allow for study of the nuclear modification independent of the p+p reference spectrum. The data from the different centrality classes are obtained from the same data run and the ratios shown in Fig. 3 are therefore largely free of systematic errors due to acceptance variations and run–by–run detector performance. The dominant systematic error comes from the determination of $\langle N_{coll} \rangle$ in the centrality bins. The shaded bands in Fig. 3 indicate the error in the calculation of $\langle N_{coll} \rangle$ in the peripheral collisions (12%). Which is a conservative upper limit on the total systemaic error. We estimate the mean number of binary collisions in the three centrality classes to be $\langle N_{coll}^{0-20\%} \rangle = 13.6 \pm 0.3$, $\langle N_{coll}^{30-50\%} \rangle = 7.9 \pm 0.4$ and $\langle N_{coll}^{60-80\%} \rangle = 3.3 \pm 0.4$.

There is a substantial change in $R_{cp}$ between $\eta = 0$ and the forward rapidities. At low pseudorapidity, the central–to–peripheral collisions ratio is larger than the semicentral–to–peripheral ratio, suggesting the increased role of Cronin like multiple scattering effects in the more violent collisions. Conversely, at forward pseudorapidities the more central ratio is the most suppressed, indicating a mechanism for suppression, that depends on the centrality of the collision. In Fig. 4 we summarize this behavior of $R_{cp}$ for the transverse momentum interval $p_T = 2.5 - 4.0\,\mathrm{GeV/c}$. A fit to an exponential form $R_{CP} \sim e^{\alpha\eta}$ yields the parameter $\alpha = -0.28 \pm 0.03$ for the central–to–peripheral ratio, and $\alpha = -0.13 \pm 0.03$ for the semicentral–to–peripheral ratio. The functional form of the central–to–peripheral ratio is remarkably close to that of the saturation scale.

The observed suppression of yield in d+Au collisions (as compared to p+p collisions) has been qualitatively predicted by several authors [14–16] within the framework of gluon saturation that includes the effect of the so called 'quantum evolution' as particles are detected away from midrapidity, although no detailed numerical predictions are yet available. These approaches also predict the observed centrality dependence of the suppression at different pseudorapidities. Other authors [17, 18] have based their predictions of nuclear modification factors on a two component model that includes a parametrization of perturbative QCD and string breaking as a mechanism to account for soft coherent particle production, using the HIJING microscopic event generator [12]. HIJING uses the effect of 'gluon shadowing' as a method of reducing the number of effective gluon–gluon collisions and hence the multiplicity of charged particles at lower $p_T$, and also includes an explicit cutoff parameter for mini–jet production. The HIJING model has been shown to give a good description of the overall charged particle distribution in d+Au collisions [19, 21], and thus the low–$p_T$ behavior

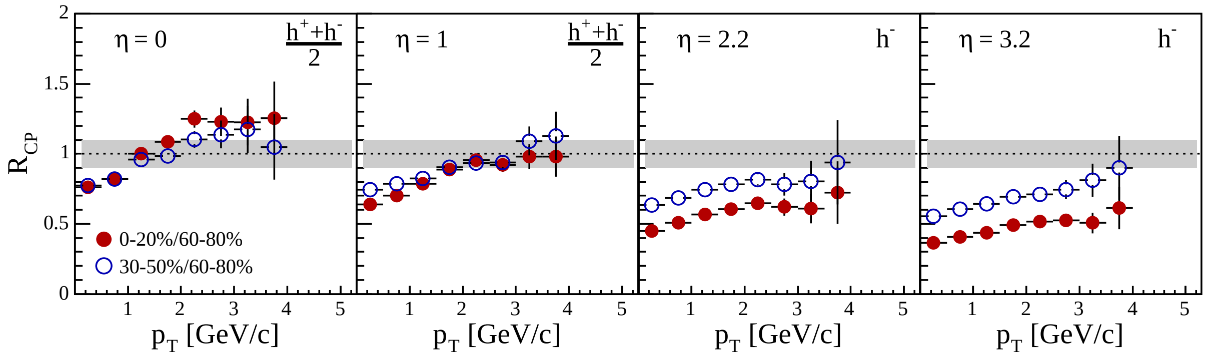


FIG. 3: Central (full points) and semi-central (open points) $R_{cp}$ ratios (see text for details) at pseudorapidities $\eta = 0, 1.0, 2.2, 3.2$. Systematic errors ($\sim 5\%$) are smaller than the symbols.

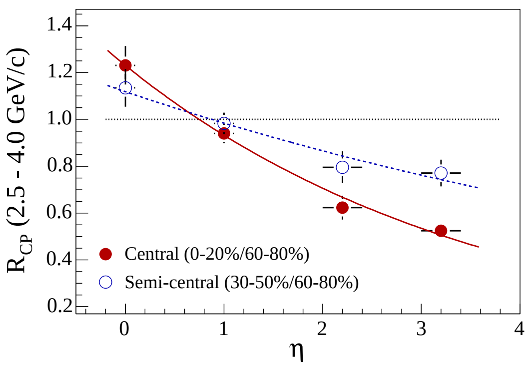


FIG. 4: Evolution of the central/peripheral (full points) and semicentral/peripheral (open points) $R_{cp}$ ratios on pseudorapidity.

of $R_{dAu}$ with pseudorapidity.

In summary, we have observed a significant reduction of the yield of charged hadrons measured in d+Au collisions, as compared to scaled p+p collisions at forward pseudorapidities. This suppression, which is absent at midrapidity, increases smoothly with pseudorapidity, i.e. as the difference in rapidity between the detected particles and the gold ion increases. Also, the change from mid– to forward rapidities is stronger for central collisions than for semi–peripheral collisions, indicating a dependence on the geometry of the collision. These results are consistent with a modification of the gold wave function as it is probed at small–$x$ values. Such modification produces a suppression at all values of $p_T$ similar to the one observed when comparing multiplicity densities. This contrasts to the situation around midrapidity where such suppression was found to be unimportant [10, 22]. While the theoretical framework for understanding the details of the observed phenomena needs further development, we note that the effects are in qualitative agreement with the predictions of the color glass condensate theory.

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